Boost DC-DC Converter Based Balancing System for Lithium-Ion Battery Pack in Electric Vehicles

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Abstract
The lithium-ion battery is the most widely used battery on the market due to its superior performance over other batteries. The capacity of lithium-ion battery packs directly influences the driving range and dynamic ability of electric vehicles (EVs). However, due to internal and external factors, inconsistency issues arise, reducing the pack capacity. Overcharged cells can explode, and undercharged cells shorten the battery's lifecycle. A proper balancing circuit is required to deal with cell inconsistency. To address inconsistency issues, this paper proposes a power converter-based cell balancing circuit. The proposed charge balancing method is implemented on a series connection of three lithium-ion battery cells and charged using the constant current constant voltage approach. The voltage of each cell is monitored and compared with the nominal voltage value at the end of constant current mode of charging. When they are not equal, the balancing circuit is activated. After balancing is done, the charging process is carried out in constant voltage mode until the desired voltage level is reached. The proposed balancing system demonstrates an efficient and automated method for balancing battery cell voltages, hence improving battery safety and life cycle.

Keywords: Active cell balancing, boost converter, Constant Current Constant Voltage charging, Electric Vehicle, Lithium-Ion battery.

I. Introduction

Electric vehicles have reduced pollution and noise levels compared to traditional gasoline-powered transportation, which has prompted a surge in demand for EVs in recent decades [1]. EVs will play an important part in transportation in the future because the globe is confronted with issues such as global warming, pollution of the air and the depletion of fossil resources. Lithium-ion batteries have attracted worldwide attention in the areas of energy storage due to its exceptional characteristics of greater energy density, small self-discharge and extended cycle life [2]. The Lithium-Ion battery is one of the most important aspects of electrification and zero-emission transportation [3].

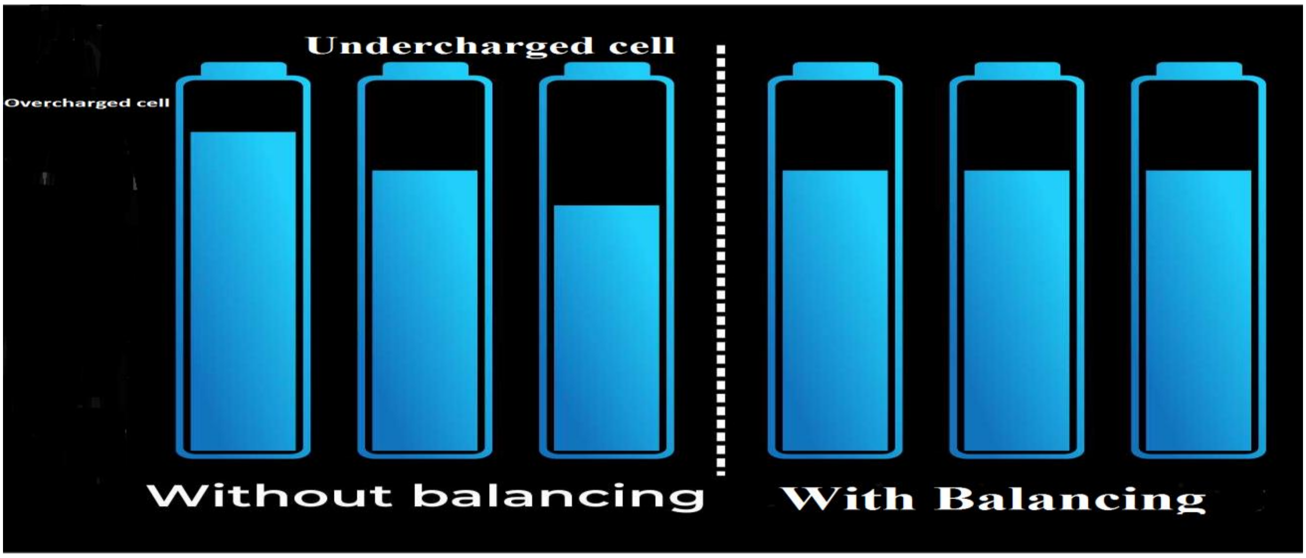

Fig. 1. Cell balancing

To achieve a higher voltage, three cells are connected in a serial sequence to form a battery pack [2]. However, the charging process must come to a halt once one cell has been fully charged, and the discharging process must come to a halt once one cell has been fully discharged. To ensure a safe and effective use, the Battery Management System (BMS) performs charge voltage equalization [3], as shown in Figure 1.

In order to determine unbalancing issue, the average voltage of three cells is measured and compared with the sum of nominal voltage of three cells. When both are not equal, the abnormal condition either under voltage problem or overvoltage problem is occurred. Then, the converter-based balancing circuit is activated to balance the voltage of three cells in the battery pack. As a result, the maximum capacity of the battery pack is achieved.

II. Overview of Proposed System

The proposed system is divided into three parts such as series connected battery cells, boost DC-DC converter and BLDC motor [8]. Fig. 2 depicts the block diagram of the proposed system to implement voltage equalization scheme.

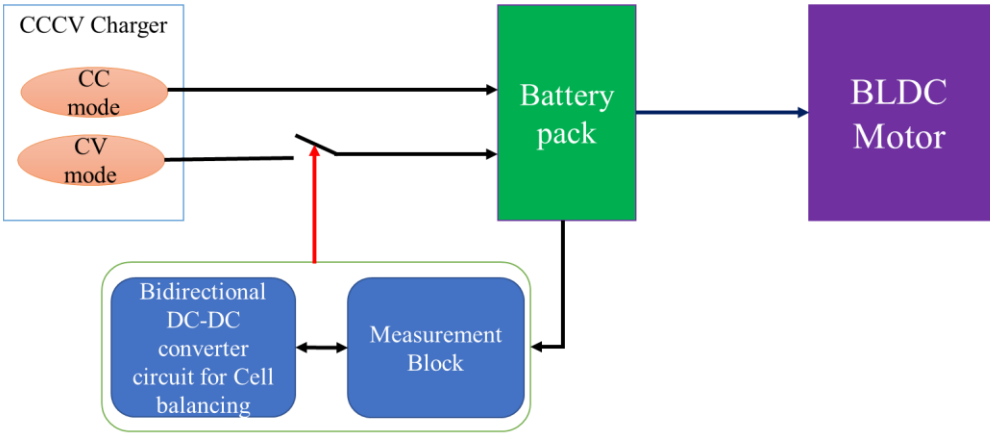

Fig. 2. Block diagram of proposed balancing system for series connected battery pack

A control function selects an unbalanced cell based on a preset value of the battery voltage levels to complete the equalization route. It operates by sending a pulse to the switch to form a communication with the bidirectional converter. The entire process is primarily focused on cell monitoring and balancing [4-7]. Hence, the maximum battery capacity is discharged in order to effectively run the motor.

III. Charging Method

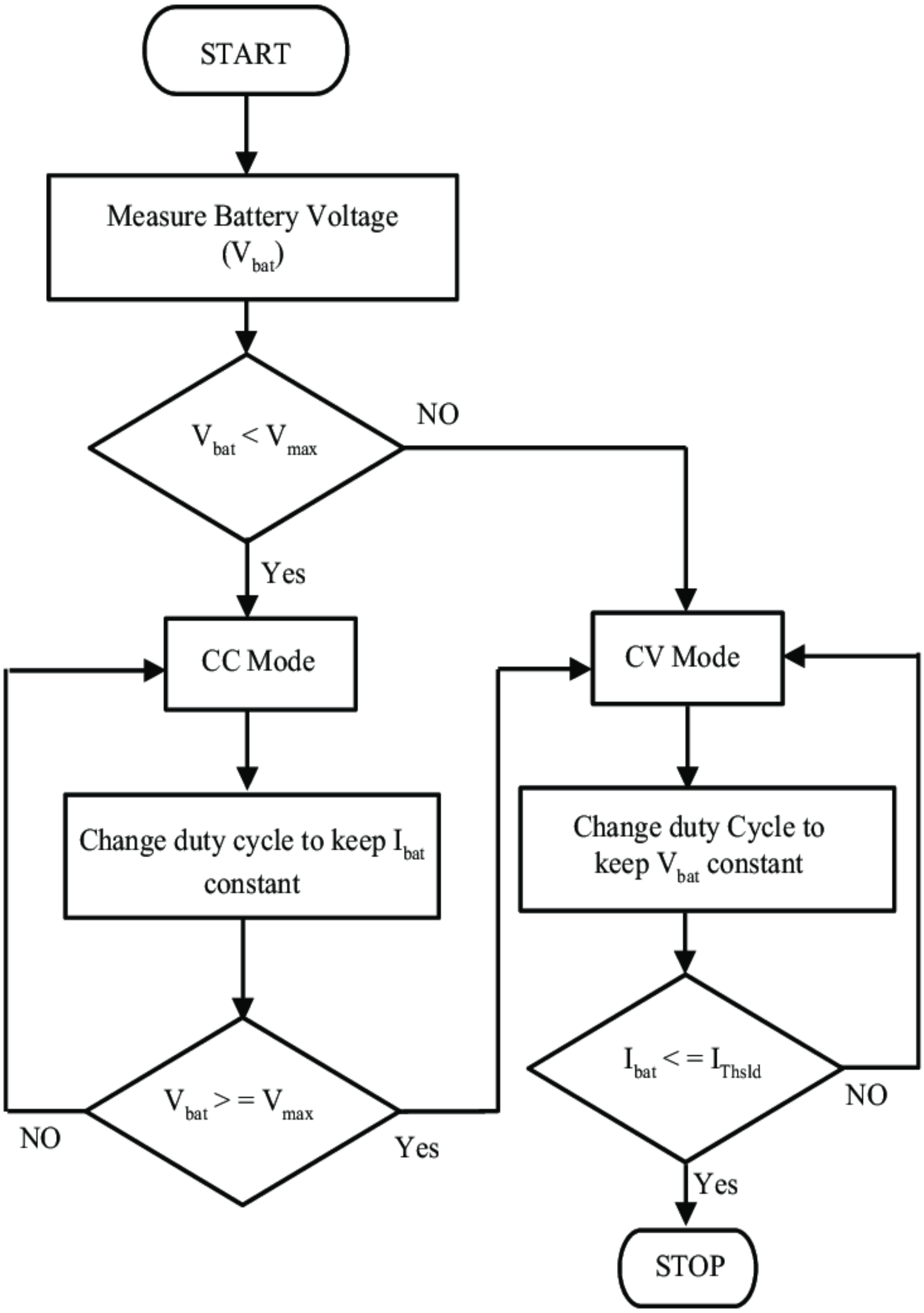

Fig. 3. CCCV method of charging

The battery pack comprises of three battery cells is charged by constant current constant voltage (CCCV) method as shown in Fig. 3. During constant current (CC) mode, the cells are charged with a constant current rate according to battery's data sheet. At the end of CC mode, the abnormal cell and the voltage difference between all three cells are determined at first. When the voltage difference among the cells exceeds 0.05V, the balancing mechanism kicks in. The abnormal cell with the minimum voltage in the pack is balanced by the boost converter. After that, a battery is charged with a predefined voltage value as specified in datasheet until they are fully charged. When all the battery cells in the pack are charged, the charging process is terminated. After cell balancing, each cell connected in series achieves the same state of charge (SOC) [9].

IV. Balancing Algorithm

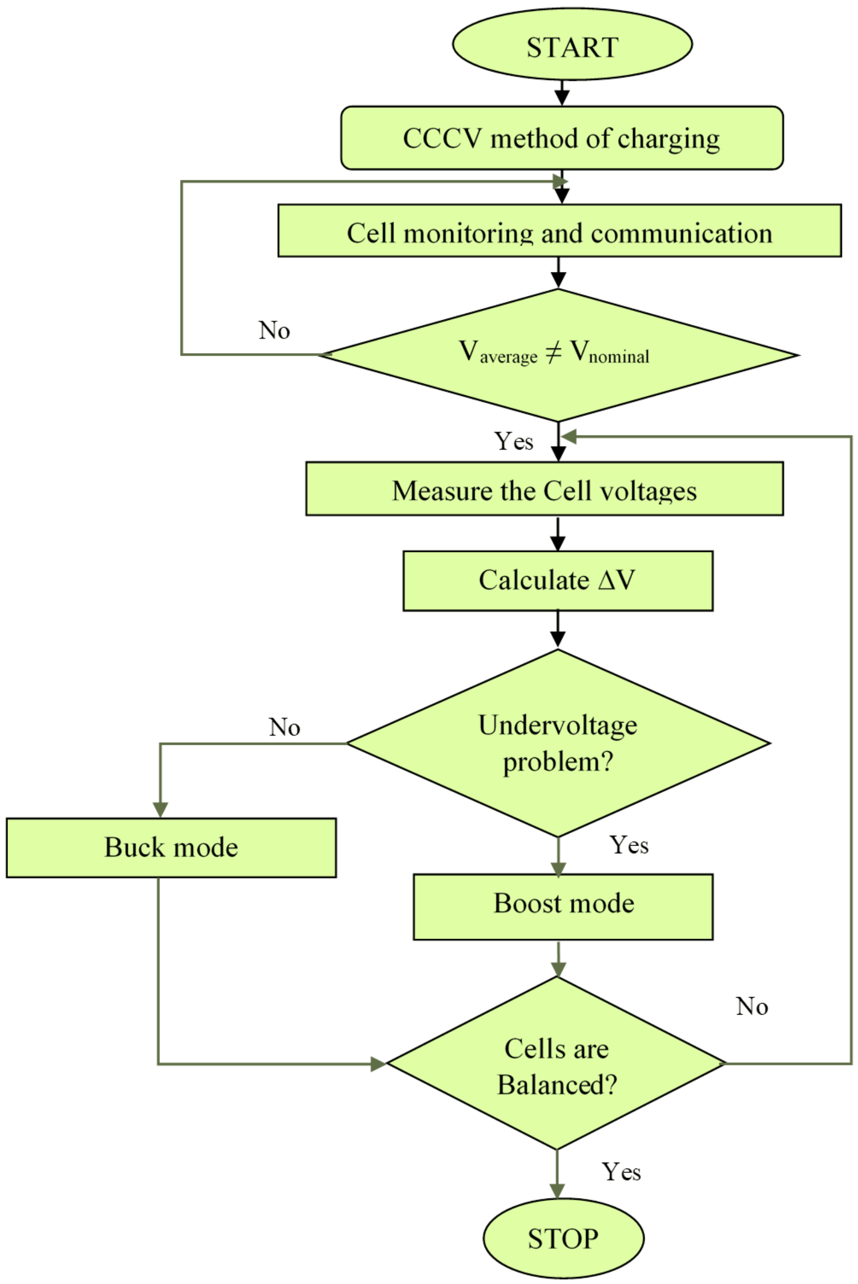

Fig. 4. The proposed balancing algorithm

Series connected three battery cells, boost DC-DC converter, and control function are the three parts of the active equalisation circuit for balancing the voltage of three cells [11]. To provide the required voltage and power, three battery cells are connected in sequence [1]. Every cell is connected to a switch that connects cell with the converter. The battery pack is connected to a boost DC-DC converter, which provides the equalization current to unbalanced cell in the battery pack [10]. The entire process is illustrated in Fig. 4.

A. Steps for equalization process

The flowchart in Fig. 4 depicts the control algorithm for balancing the voltages of lithium cells connected in series. The switch is acts as ideal switch during ON or open during OFF for smooth operation, the diode acts as ideal switch, and the boost converter is ideal current source for smooth operation. The operations are as follows:

1. Start the CCCV method of charging.
2. Continuously monitoring the cell voltage and communicate to PI controller.
3. Calculate the average voltage value of three battery cells to find whether the cell is normal (or) abnormal cell.
4. Compare the average value with the battery’s nominal voltage.
5. Calculate the voltage difference ΔV
6. If $\Delta V \geq 0.05V$, the cells are unbalanced. Activate Balancing circuit.
7. Determine whether the unbalancing is occurs due to undervoltage or overvoltage problem. Boost converter is used to solve the undervoltage problem.
8. Finally, the cells are balanced.

V. Battery Cell Balancing System

The proposed system comprises the Lithium-Ion battery pack, DC-DC converter and BLDC Motor is described below with their design optimization.

A. Lithium-Ion battery pack

The positive and negative electrodes, as well as the electrolyte are three primary functional components of a battery. The negative electrode (anode) of a traditional lithium battery cell is usually made of carbon whereas positive electrode (cathode) is typically a metal oxide; the lithium salt is used as an electrolyte [3]. Between anode and cathode, the electrodes' electrochemical roles are reversed based on the current flow direction through the battery.

Table I: Battery cell specifications

Parameters	Value
Nominal Voltage	3.7V
Battery capacity	2.6 Ah
Usable state of charge	10%-100%
Maximum charge voltage	4.3V
Standard discharge current	1.32A
Internal Resistance	0.014
Maximum usable capacity	2.4 Ah

Graphite is the most widely used anode in battery industry. Heat exposure and fast charging accelerate the battery degradation faster than aging [13]. The battery in a Nissan, for example, will degrade twice as quickly as the battery in a Tesla because it lacks an active cooling system [12]. The lithium-Ion battery cell specifications are presented in Table I.

B. Boost DC-DC Converter

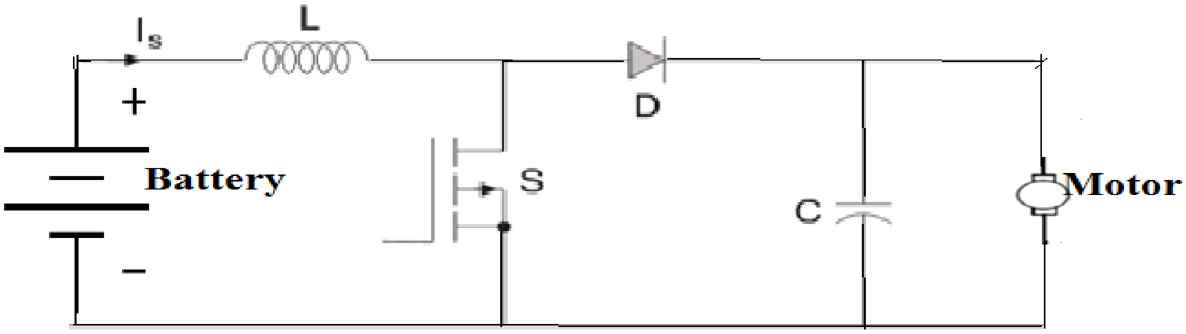

Fig. 5. Boost DC-DC converter

The Boost converter has two modes of operation. When the switch is ON, the energy stored in the inductor. Inductor stored energy is released when switched OFF the MOSFET switch [15]. Fig. 5 depicts the boost converter model.

The duty ratio of pulses influences the value of output voltage in boost converter.

$$D = \frac{t_{on}}{t_{on}+t_{off}} = \frac{t_{on}}{T} \quad (1)$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (2)$$

Converter operation:

Mode I: Switch is ON, Diode is OFF

According to Fig. 6, the switch is turned on, indicating the voltage source and inductor forms a closed circuit for current flow. During this mode of operation, the switch is turned on when T=T_{ON} and then turned off when T=T_{OFF}.

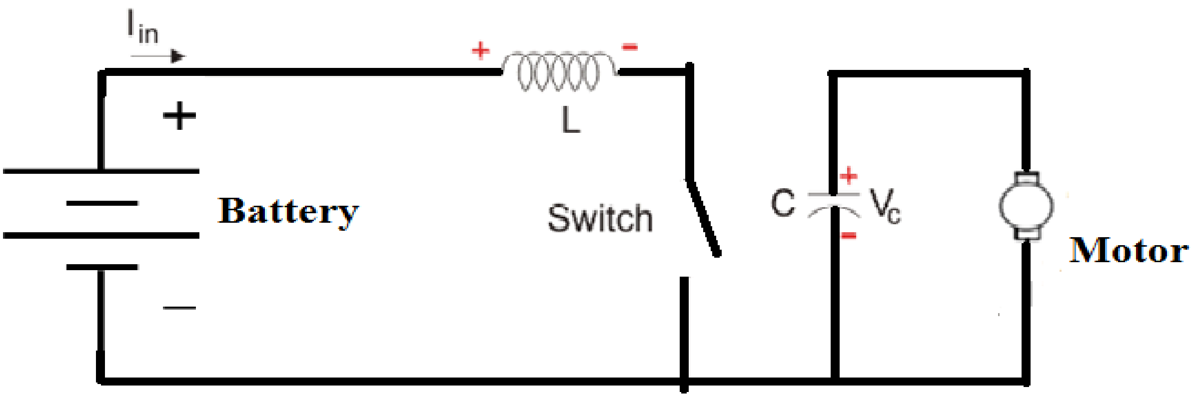

Fig. 6. Equivalent circuit for mode I

The time period T is calculated by equation 3.

$$T = T_{ON} + T_{OFF} \tag{3}$$

Switching frequency is

$$f_s = 1/T \tag{4}$$

The duty cycle is defined by equation 5,

$$D = \frac{T_{ON}}{T} \tag{5}$$

According to Kirchoff's law, the voltage across the inductor is equal to input voltage.

. $$V_{input} = V_L \tag{6}$$

$$V_L = L\frac{di_L}{dt} = V_{input} \tag{7}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{input}}{L} \tag{8}$$

Mode II: Switch is OFF, Diode is ON

In this mode, the polarity of the inductor is reversed, as shown in Fig. 7. The output voltage is boosted because the inductor is now considered as an additional source with the input source, the inductor energy is released and finally given to the load, which helps to flow the current in the same direction through the load.

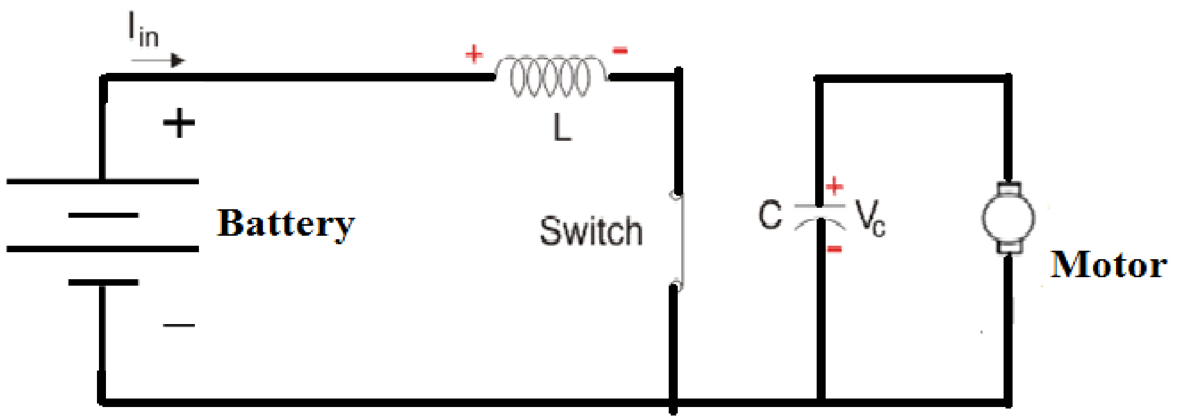

Fig. 7. Equivalent circuit of mode II

According to KVL, the mode II operation is represented by the equations (9-11).

$$V_{in} = V_L + V_0 \tag{9}$$

$$V_L = L\frac{di_L}{dt} = V_{in} - V_0 \tag{10}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_{in}-V_0}{L} \qquad (11)$$

Switch is open during T_{OFF} which is calculated by equation 10.

$$T_{OFF} = (1 - D)T \qquad (12)$$

C. BLDC Motor Drive

In today's world, battery-fed electric drives are widely used for EV applications, such as load leveling, transient operation, and power recovery during braking. To meet these requirements, boost power flow converters are essential to connect the battery pack with the motor drive system's dc connection [14]. The power flow in normal mode is from the battery to the motor, whereas the motor's mechanical energy is converted into electrical energy and given to the battery for storage in the regenerative braking mode.

VI. Simulation Results and Discussion

The proposed work is simulated using MATLAB/Simulink, as shown in Fig. 8. Cell balancing play a vital role in battery management system.

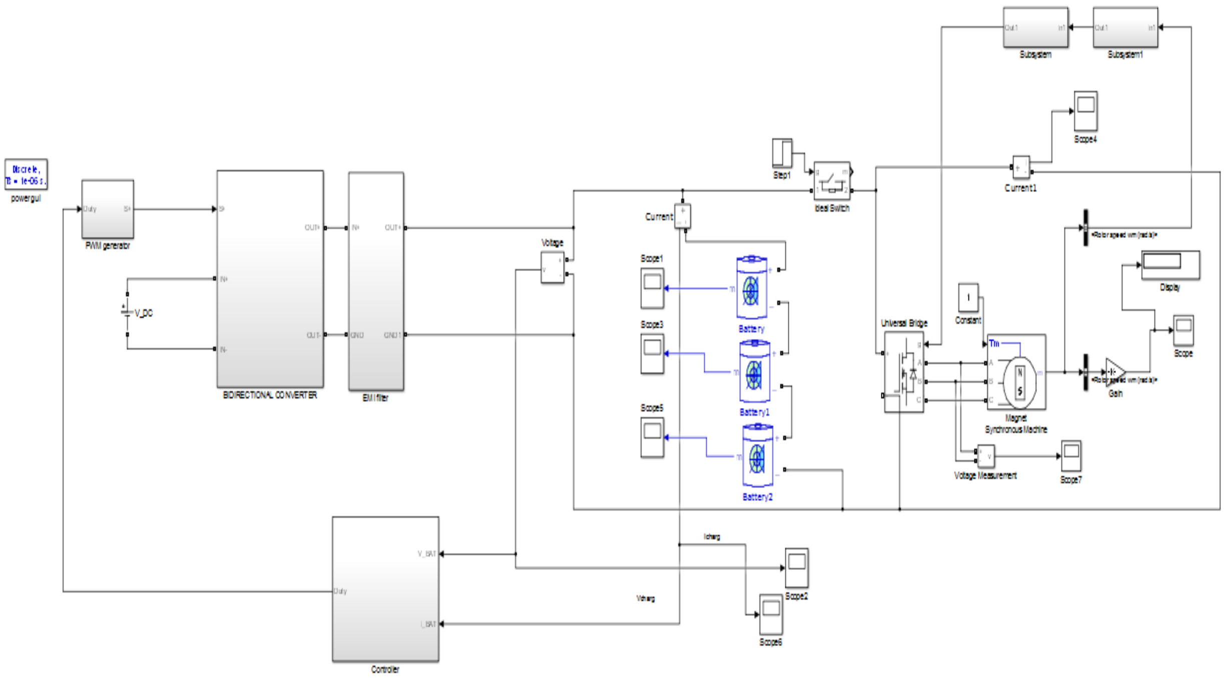

Fig. 8. Simulation of the boost converter balancing system for EV with motor

Battery cell balancing play a vital role in BMS used in EV [15-17]. The lithium-ion battery which capacity of 2.6Ah is used to verify the proposed balancing method. The converter-based cell voltage balancing circuit is developed to achieve the higher voltage of a battery pack involves three cells in series and maximum balancing current of the circuit is 5.5A. In the battery simulation, the boost dc-dc converter based active cell balancing circuit is programmed to operate at a frequency of 25 KHz and a duty cycle of 33%. Switch is used to decide the charging and discharging process. In this project I_{charge} is compared to I_{ref}. When I_{charge} is less than the I_{ref} , then charging process takes place. If I_{ds} is compared to I_{ref} . I_{ds} is greater than I_{ref} , then discharging process takes place.

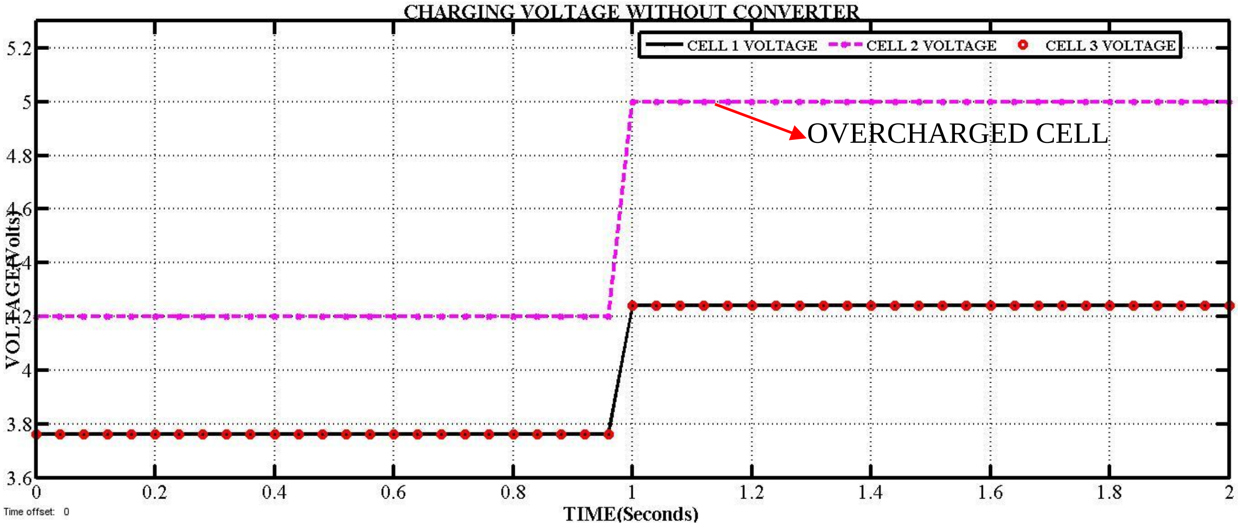

Fig. 9a. Unbalanced voltage of three cells

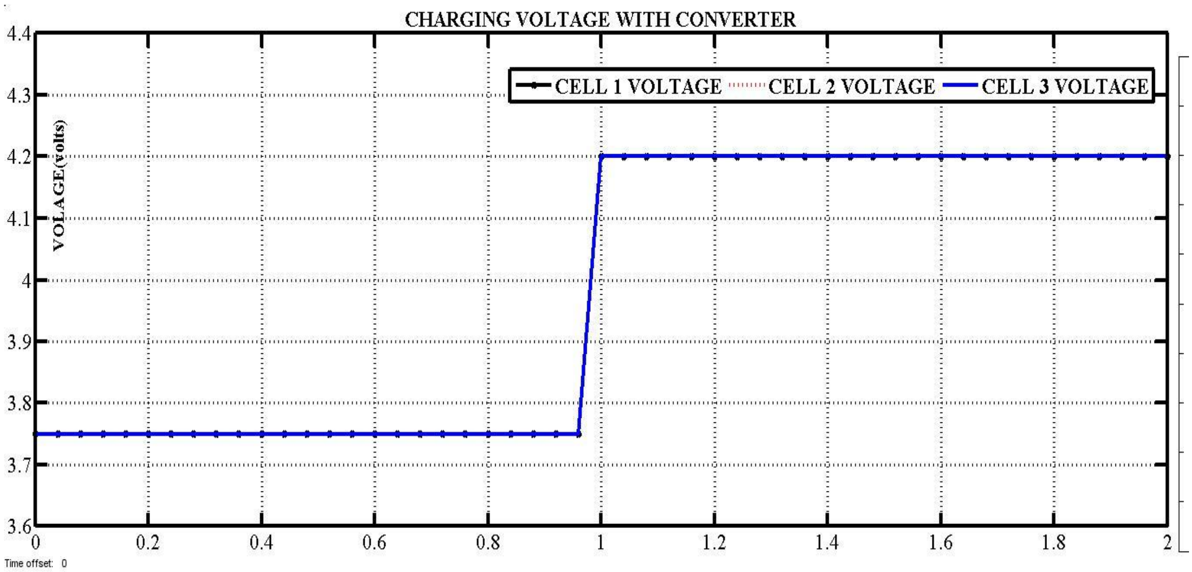

Fig. 9b. voltage of three cells during charging with active balancing circuit

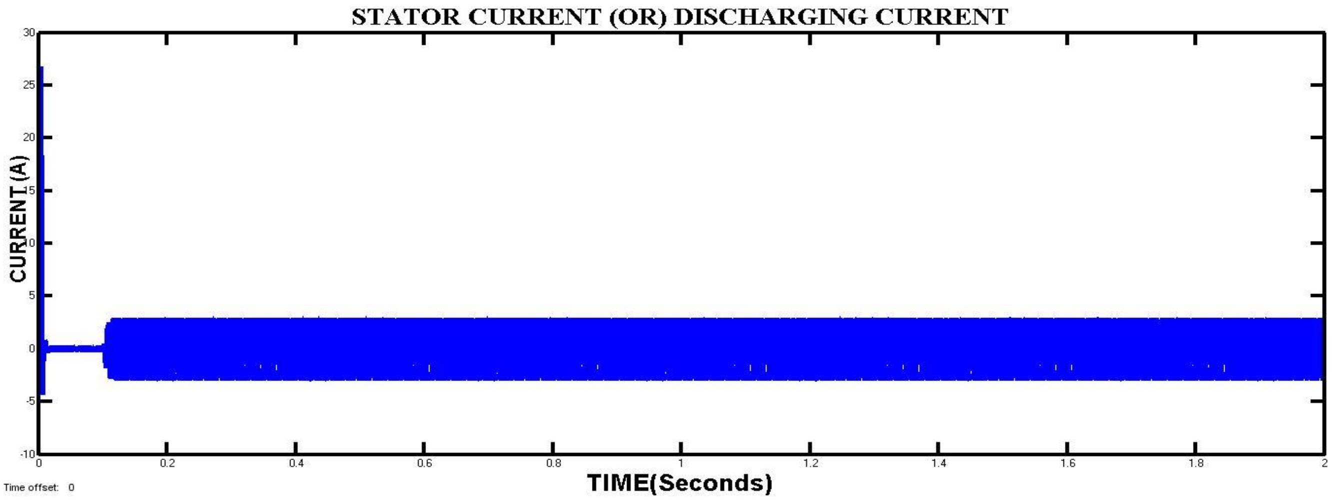

Fig. 10. Discharging current from BLDC motor

In this paper, the voltage equalization takes place for equalizing the 3 battery cells connected in a series manner. CCCV charging method is used with active balancing circuit. At first, the comparison has been done between the current flows through the battery cell and the reference current. Fig. 9 explains the overcharged cell is not allowed to charge by getting equalization from the converter. The maximum voltage of battery cell is 4.2V but cell 2 having the voltage of 5V due to overcharging problem. From the result, it explains that three cells are equally charged by balancing algorithm. From the analysis, it is worthy mentioned that the proposed balancing algorithm accomplishes the fast and accurate cell balancing. When the voltages are balanced, the battery will discharge to supply the load, as represented in Fig. 10. When a voltage source is enabled, the battery charging takes place and the load can supply from the voltage source.

VII. Conclusion

The voltage equalization control algorithm is proposed for equalizing three battery cells which are connected in series to achieve higher voltage. The simulation results obtained from the proposed equalization control algorithm using boost converter are shown. The results show that this algorithm's balancing process is simple to implement and has a faster response time. Moreover, the output of the proposed method shows precise voltage balancing, the cell voltage levels are maintained within the safe operating area. The design of cell balancing controller is demonstrated in this study using only three series connected Li-Ion battery cells. But the proposed voltage balancing method can be extended to balance large number of cells used for automotive energy storage application, particularly in electric vehicles.

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